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NEXT GENERATION EARTH-TO-ORBIT SPACE TRANSPORTATION SYSTEMS

UNMANNED VEHICLES

&

LIQUID/HYBRID BOOSTERS

Uwe Hueter

George C. Marshall Space Flight Center
Program Development
Space Transportation & Exploration Office

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NEXT GENERATION EARTH-TO-ORBIT SPACE TRANSPORTATION SYSTEMS

UNMANNED VEHICLES & LIQUID/HYBRID BOOSTERS

by
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Abstract

The United States civil space effort when viewed from a launch vehicle perspective tends to categorize into the pre-Shuttle and Shuttle eras. The pre-Shuttle era consisted of expendable launch vehicles where we matured a broad set of capabilities in a range of vehicles, followed by a clear reluctance to build on and utilize those systems. The Shuttle era marked the beginning of the U.S. venture into reusable space launch vehicles and the consolidation of launch systems used to this one vehicle. This led to a tremendous capability, but utilized man on a few missions where it was not essential and compromised launch capability resiliency in the long term.

Launch vehicle failures, between the period of August 1985 and May 1986, of the Titan 34D, Shuttle Challenger and the Delta vehicles resulted in a reassessment of U.S. launch vehicle capability. The reassessment resulted in President Reagan issuing a new National Space Policy in 1988 calling for more coordination between federal agencies, broadening the launch capabilities and preparing for manned flight beyond the Earth into the solar system. As a result, the Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA) are jointly assessing the requirements and needs for this nation's future transportation system. Reliability/safety, balanced fleet and resiliency are the cornerstone to the future.

This paper provides an insight into the current thinking in establishing future unmanned earth-to orbit (ETO) space transportation needs and capabilities. The paper presents a background of previous launch capabilities, future needs, current and proposed near term systems and system considerations to assure future mission needs will be met. The paper focuses on propulsion options associated with unmanned cargo vehicles and liquid booster required to assure future mission needs will be met.

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Introduction

Effective space exploration requires reliable transportation, a balance of good science, and a progressively expanding space infrastructure starting with the Space Station. Adequate, reliable, lower cost space transportation is a key to the nation's future in space. Primary in the critical near term, is making more effective use of the systems we have and evolving a few early flexibility enhancements.

Launch vehicle failures, between the period of August 1985 and May 1986, of the Titan 34D, Shuttle Challenger and the Delta vehicles resulted in a reassessment of U.S. launch vehicle capability. Also, the country's total reliance on the Space Shuttle (SS) for all manned transportation and the majority of the unmanned satellites was questioned. The reassessment resulted in President Reagan issuing a new National Space Policy in early 1988, changing the nation's space transportation policy. The policy calls for more coordination between federal agencies, broadening the launch system base for assured access, and sets as a national goal manned flight beyond the Earth into the solar system. As a result, the Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA) are jointly assessing the requirements and needs for this nation's future transportation system. Reliability, fleet balance and resiliency are cornerstone to the future.

The Space Shuttle will remain the primary manned access to space for many years and upgrades are planned to improve reliability, safety, and operational efficiencies. Key among these upgrades are: development of an Advanced Solid Rocket Motor (ASRM) to provide improved reliability through redesign and advanced manufacturing facilities; continuing design and process adjustments to our current solid rocket motor; and completing the Space Shuttle Main Engine (SSME) new high pressure turbopumps along with other select design improvements to address every critical failure mode. Other areas of key improvement are: upgraded state-of-the-art Orbiter subsystems such as avionics; additional crew escape capability; potential design improvements in the external tank; and launch/turnaround/flight operational changes to reduce cost per flight.

Acknowledgement for contributions to this paper is given to Mr. Tom Mobley from Martin Marietta Corporation and Dr. James Steincamp & Mr. David Taylor from NASA/MSFC.

In addition, added flexibility is needed in transportation systems by the late 1990s, including addition of: heavy lift capability complementary to the Space Shuttle to assure delivery of Space Station transportation node hardware, lunar and planetary vehicles, and other key payloads; an additional Orbiter to provide downtime for servicing and protect the fleet capability from significant mission disruptions; and an assured crew return vehicle (ACRV) for safe return of the crew from Space Station Freedom. Early requirements could be met by a vehicle such as Shuttle-C. Post year 2000 requirements will establish a need for a new unmanned modular, low cost launch vehicle such as the Advanced Launch System (ALS) and perhaps new liquid or hybrid rocket boosters for mission reliability, safety and flexibility. The exact timing of each needs focus, but certainly system understanding should mature and major steps need to continue in related technologies through our base technology and test bed efforts along with the directed technology initiatives planned by both the NASA and the AF.

It is clear that national space activities should take advantage of the many unfolding opportunities through a balanced science and infrastructure program. Transportation systems remain a vital enabling ingredient in accomplishing these objectives. It is time now to continue moving ahead on a course of continuity and challenge.

This paper provides an insight into the current thinking in establishing future unmanned earth-to orbit (ETO) space transportation needs and capabilities. The paper presents a background of previous launch capabilities, future needs, current and proposed near term systems and system considerations to assure future mission needs will be met. The paper focuses on propulsion options associated with unmanned cargo vehicles and liquid booster required to assure future mission needs will be met.

Lessons Learned

The launch vehicle failures of 1985-1986, brought into sharp focus that today's launchers fall far short of the kind of near-perfect reliability expected of space transportation vehicles. Figure 1 summarizes the experience of the world's major launch vehicles, past and present. The term "success ratio" rather than reliability highlights an important qualification to this tabulation: the number of launches of any one vehicle configuration is too small, from a statistical perspective, to yield an actuarially dependable reliability estimate. In particular, those vehicles with the largest number of launches have evolved from the ballistic missiles of forty years ago through both incremental and block upgrades. Moreover, the underlying data behind these summary results is an "apples and oranges" mixture, e.g. the expendable vehicle failures include some upper stage failures while the Shuttle data does not. Figure 2 depicts past launch rates. In recent years, the Soviets have been launching vehicles at a rate of approximately five times that of the rest of the world. Since the Soviets usually have one or two failures each year, there is at least ground for suspecting that reliability of current launch vehicles may approach a practical limit of approximately 0.98, i.e. one loss in every 50 launches. Figure 3 illustrates an intuitively expected trend of reliability growth with vehicle evolution: successive versions of the Titan vehicle more quickly achieved higher reliabilities than their predecessors. Similar trends have been calculated for other vehicles. Although the number of failures due to any one factor is small, there is some indication that the early failures are due primarily to redesign, while later failures relate to manufacturing and operational processes.

Launch Vehicle	Launches	Mission Failures	Success Ratio
Saturn	33	0	1.000
Atlas	495	94	.810
Titan III	152	7	.954
Delta	194	12	.938
Space Shuttle	35	1	.971
Ariane	27	5	.815
Proton (D-series)	165	18	.891

Figure 1. Launch Vehicle Success History

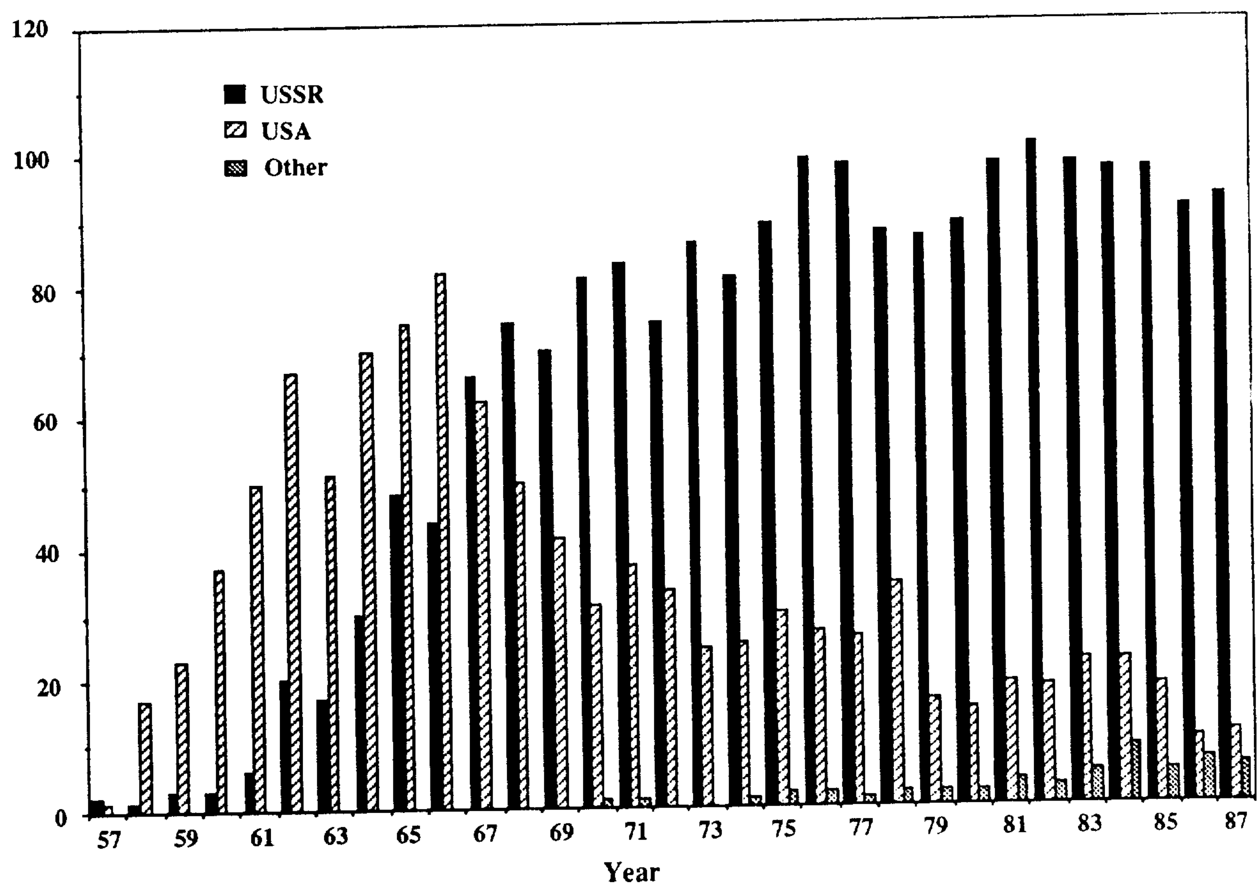


Figure 2. Annual Launches

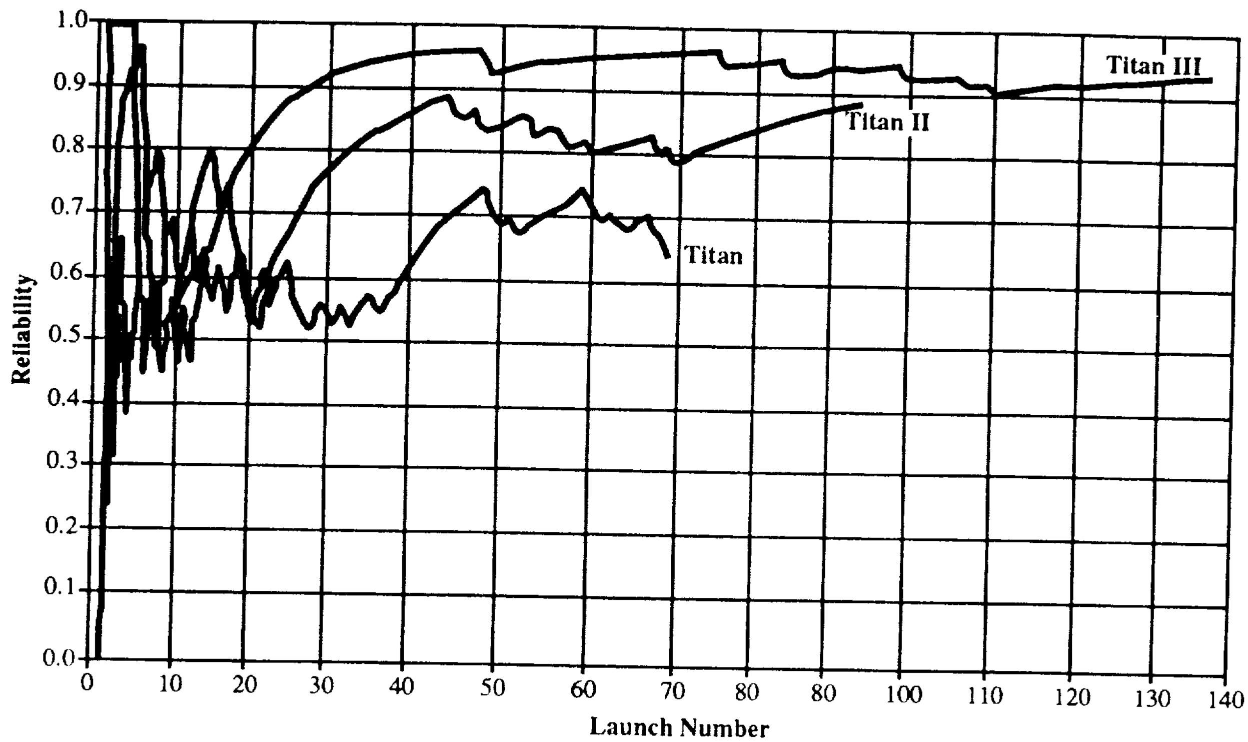


Figure 3. Reliability Estimation of Titan I, II, III

These trends have implications for the Shuttle. The initial run of 24 successful launches was a very respectable showing for a new vehicle, although longer success runs have been observed (e.g. 43 for the Delta). During the 32 month stand down following the Challenger accident, extensive improvements were made, not only in the solid boosters, but also throughout the vehicle and the supporting operational and management systems. Further, programs such as the advanced turbopump and the ASRM were undertaken or planned to further enhance the Shuttle's reliability. In the longer run, improvements which allow the SSMEs to operate at constant or reduced throttle will further improve reliability. In short, the evolution of the Shuttle has begun. Additionally, the Space Shuttle has unique advantages relative to current expendables, in the form of redundancy and abort modes which can in many situations save the crew, vehicle, and payload in the event of malfunctions. Nonetheless experience now tells us that achieving launch vehicle reliabilities greater than 0.98 is a challenge rather than an accomplishment.

The above discussion leads one to conclude that a goal to achieve a perfect launch vehicle is not a very pragmatic approach. Instead, a more reasonable approach that allows the nation to both plan and budget for eventual failures will prevent a repeat of the nation's stand down experienced after the Challenger accident. In addition, alternate vehicles to allow launching either manned or unmanned cargo would assure the nation a capability to continue operation even in the event of a catastrophic failure. Reassessment of U.S. space policy has resulted in the following objectives:

"• Assured access to space, sufficient to achieve all United States space goals, is a key element of National Space Policy

• U.S. space transportation systems must provide a balanced, robust, and flexible capability with sufficient resiliency to allow continued operations despite failures in a single system

• Goals of U.S. space transportation policy are:
  - Achieve and maintain safe and reliable access to, transportation in, and return from, space
  - Exploit the unique attributes of manned and unmanned launch and recovery systems
  - Encourage U.S. private sector space transportation capabilities without direct federal subsidy
  - Reduce costs of space transportation and related services"[1]

Budget /Cost Considerations

The estimated NASA budget requirements for the next ten years is shown in Figure 4. The budget includes the operating fund (R&PM), construction of facilities (COF), and program costs segregated into the major NASA's offices. The budget wedge for each office, except the Office of Space Flight (OSF), includes both approved programs and projected new starts. The OSF wedge only includes approved programs. The heavy dark line indicates a NASA budget growth of 15% through 1993 and 5% in 1994 and beyond. OSF potential new starts include such programs as Shuttle-C, liquid rocket booster (LRB), Space Transportation main/booster engines, space transfer vehicle (STV) and an assured crew return vehicle (ACRV). As can be seen from Figure 4, zero budget would be available to institute new initiatives if the budget growth rate is limited to 15%. This emphasizes the need for

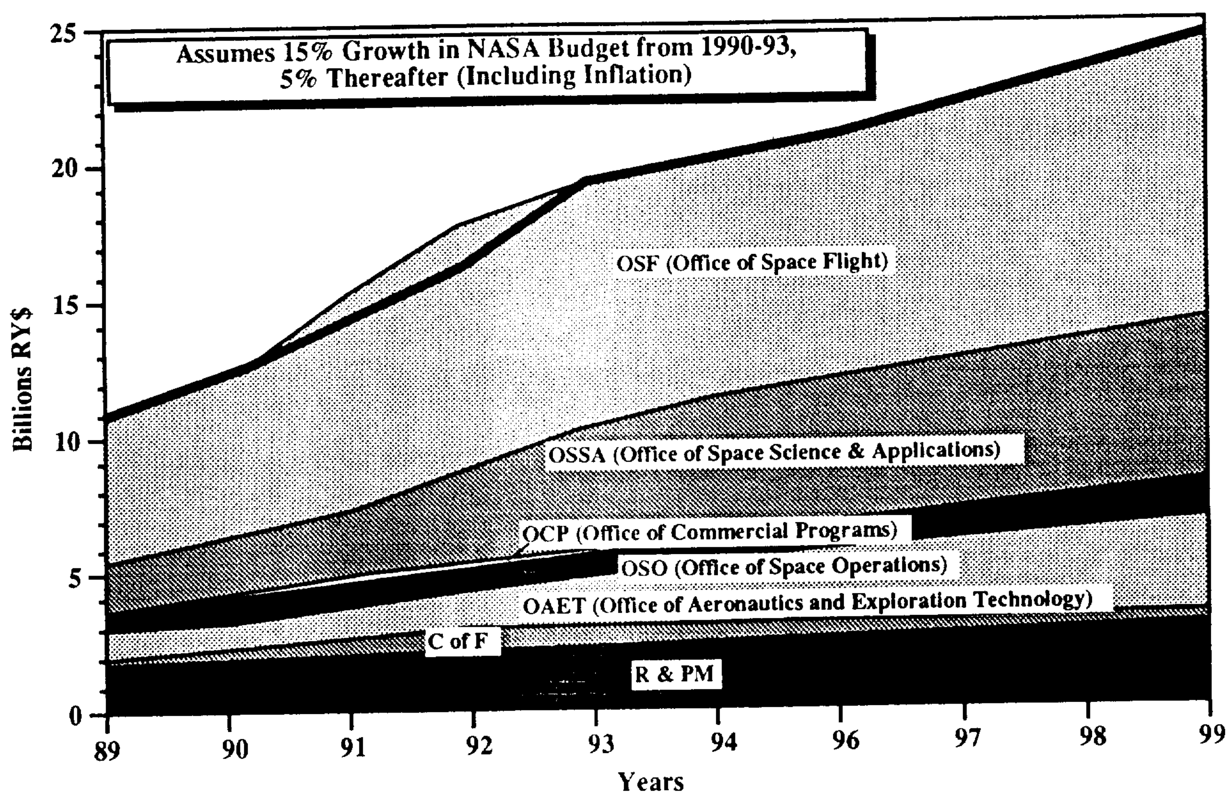
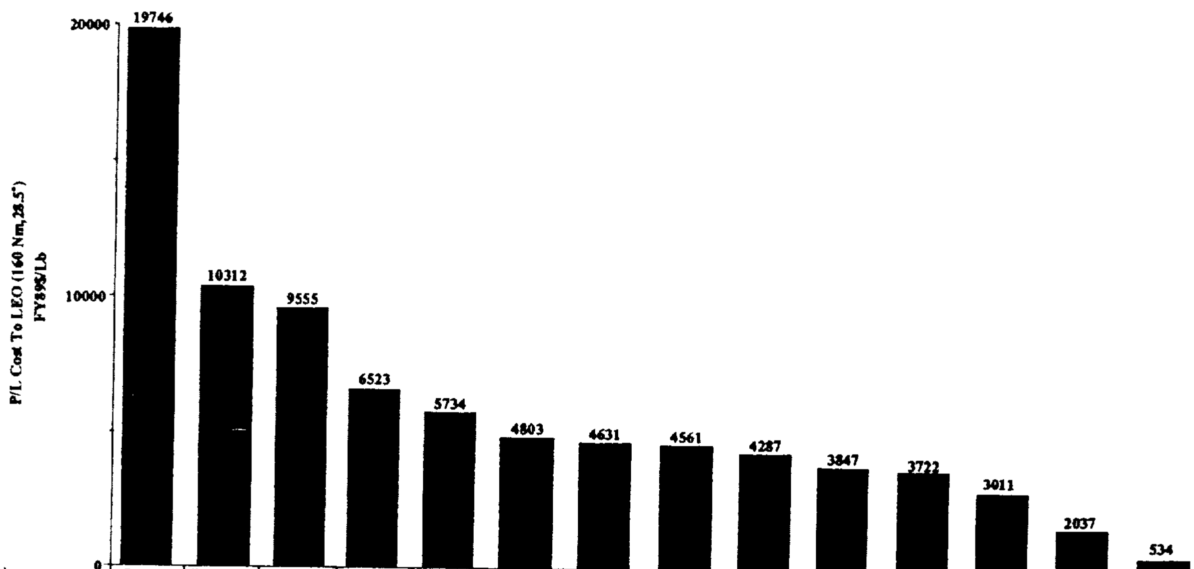


Figure 4. Space Transportation Planning Budget Wedge Analysis

[1] "Space Flight", Office of Space Flight - National Aeronautics and Space Administration, March 1989.

reducing current program recurring cost to allow a budget wedge for new initiatives. Additionally, the new starts will require low upfront investments to remain within the budget. Toward this end, investigations are currently being conducted to improve operational efficiencies of current launch systems. The average cost per flight and dollars per pound of payloads to LEO for various launch vehicles (past, present and future) are shown in Figure 5. Each bar represents each vehicle's expected matured flight rate per year. All costs shown reflect expendable hardware and operations costs and exclude the vehicle's design, development, test and engineering (DDT&E) and reusable hardware costs. As can be seen from the figure, dramatic cost reductions are anticipated for future launch vehicles.



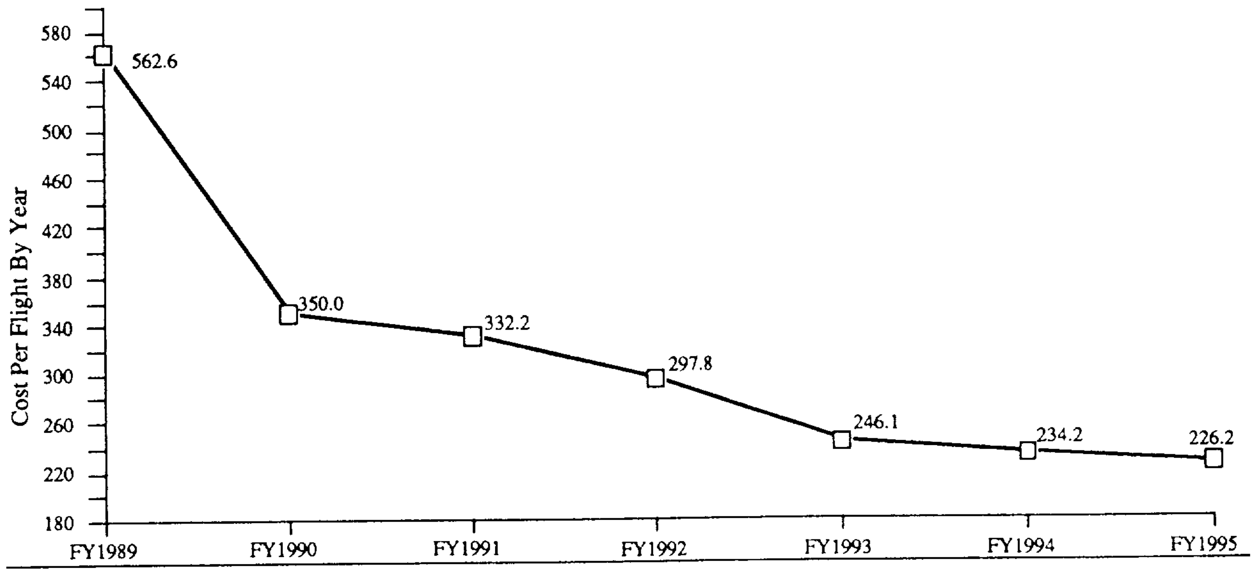
Vehicle P/L To LEO (Lbs) (160 nm, 28.50)	Scout 500	Titan II 5000	Saturn IB 31000	Delta (3920) 7400	Atlas Centaur 13200	Saturn V 249000	Shuttle Baseline 45000	Titan IV 38000	Delta II 8700	Titan III 28800	Shuttle ASRM 56000	Sh-C(2E) 89000	Sh-C(3E) 147300	ALS OBJ 150000
Assumed Flt Rate	4	5	2	4	4	2	14	10	12	5	14	3	3	20
Avg Cost Per Flt (89$/M)	10	52	296	48	76	1196	208	173	37	111	208	268	300	80

Note: Above Estimates Include Expendable Hardware And Operations (Exclude DDT&E And Reusable Hardware)
Both Fixed And Variable Operational Costs Are Included
Shuttle-C Estimate Includes Shuttle-C Unique Fixed Costs And Variable Cost And Excludes Common Shuttle
Fixed Cost (i.e. Marginal Cost). Based On Alternating Flights Of 3 Engine And 2 Engine Configurations Respectively.

Figure 5. Launch Vehicle Operations Cost Estimates

The current Space Shuttle cost per flight and the projected reduction is shown in Figure 6. The breakout of the projected cost per flight for the Space Shuttle is shown in Figure 7. As can be noted from the figure, operations cost constitute a major percentage (43.9%) of the total projected cost per flight. This figure is based on a flight rate of 14 flights per year.

The question of reusable versus expendable launch systems is always a major cost consideration in the initial phases of a new design. The argument has been that reusable launch vehicles, although higher in DDT&E cost, are more cost effective than expendable vehicles based on the longer term. To support the argument of reusability, Figure 8 provides a cost comparison for the projected cost of the Space Shuttle SRBs. Included in the cost is the refurbishment cost for the SRBs. As can be seen, a cost savings of approximately $56 million can be achieved by recovering rather than expending the boosters. Thus, the trend of future vehicles will be to recover the major elements of the system.



Flight Rate	4	9	10	11	13	13	13

Figure 6. Space Shuttle Cost Per Flight Projection (Millions of FY 1989 Dollars)

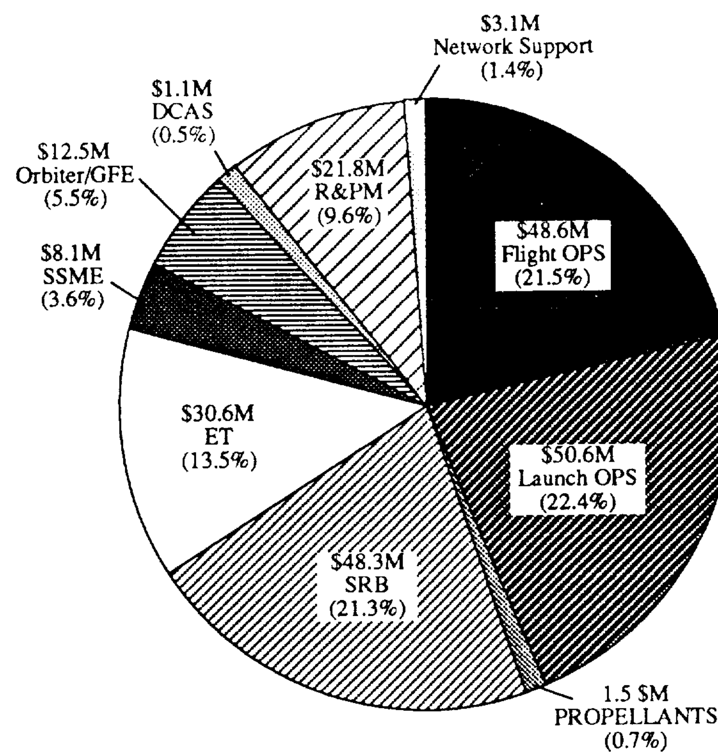


Figure 7. Space Shuttle Cost Per Flight (Millions of FY 1989 Dollars)
$226M/Flight in 1995

	Recovered/Refurbished Per Flight Set (2 Units)	New Per Flight Set (2 Units)	DELTA Cost
SRM	$28,390,000	$47,490,000	$19,100,000
BAC	$11,860,000	$49,760,000	$37,900,000
KSC Costs	$1,000,000	$0	($1,000,000)
Total	$41,250,000	$97,250,000	$56,000,000

Figure 8. SRB Cost: Mid 90's (Millions of FY 1989 Dollars)

The budget environment, along with NASA's current needs, indicates that the potential for new starts will be severely limited for many years. The few new starts that will be approved for NASA will most likely require non-optimum (stretched) development schedules to reduce near term funding profiles.

Early And Long Term Mission Needs

The Civil Needs Data Base (CNDB) is a projection of the civil space transportation requirements for the time interval 1990 thru 2010. The current version of the CNDB is referenced as CNDB '90. There are presently two options included in the CNDB '90, the base mission model and the expanded mission model which includes the Space Exploration Initiative (SEI). Figure 9 graphically shows the projected range of mass required to be launched into low earth orbit. In terms of total mass

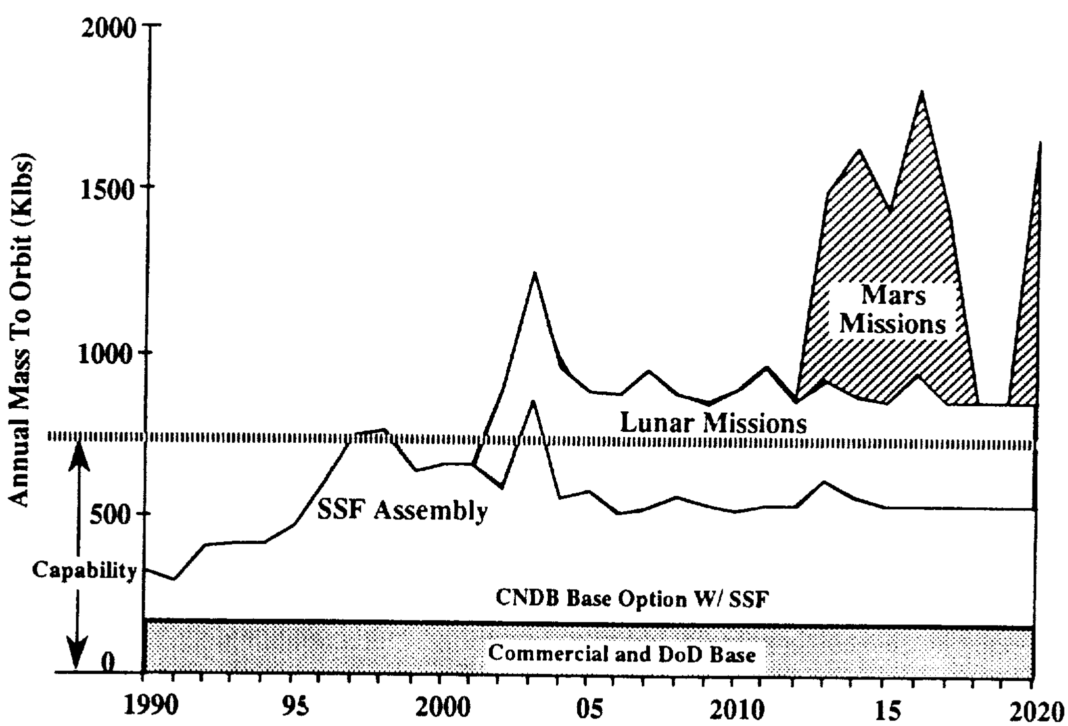


Figure 9. Space Transportation Requirements Forecast

required to be delivered to low earth orbit, the SEI missions (Mars and Lunar) are clearly the most demanding. As noted on Figure 9, additional launch capability will be required. Some of the infrastructure requirements for SEI missions are:

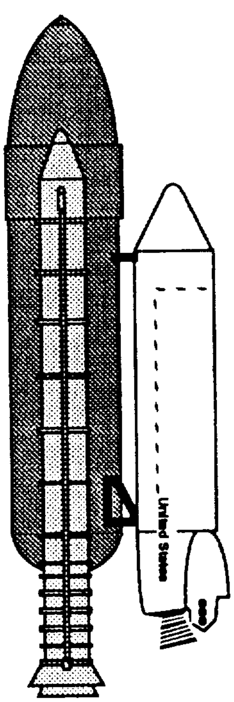
- A heavy lift launch vehicle (HLLV)
- Earth orbit facilities for assembly and support
- Mars & Lunar transfer systems
- Science payloads and equipment

Future Systems Studies

Unmanned Vehicles

Future unmanned transportation systems such as Shuttle derived vehicles (SDV), sidemounted and inline cargo carriers, and Advanced Launch Systems (ALS) are being studied. The Lunar/Mars missions definitely will require an HLLV to maintain the flight rates and orbital assembly to a minimum.

NASA is currently analyzing various SDV evolution paths to establish the desired direction for future unmanned launch vehicles. One SDV heavy lift concept currently being studied for the late 1990's is the Shuttle-C, see figure 10. The Shuttle-C is a largely expendable, unmanned launch system capable of carrying payloads of 85,000-150,000 pounds to low earth orbit. Shuttle-C is not a new system, but rather an expansion of our current Space Shuttle Program. It uses existing and modified



- **Standard 4-Segment SRB's (Reuseable)**
- **Standard ET (Expendable)**
- **Orbiter Boattail (Expendable)**
  - 2 SSME's (Remove SSME #1)
  - Remove Verticle Stabilizer
  - Remove Body Flap
  - Cap SSME #1 Feedlines
  - OMS Pods (Do Not Install OME's, RCS Tanks And 4 RCS Thrusters/Pod)
  - RCS Performs Circularization And Deorbit
  - Cover And Thermally Protect SSME #1 Opening
- **Payload Carrier (Expendable)**
  - New Shroud/Strongback
  - Skin/Stringer/Ringframe Construction Of Al 2219
  - 15' X 82' Useable Payload Space
  - 15' X 60' Changeout On Pad Capability
- **Avionics**
  - Uses Mature Design Components From STS And Other Applications
  - Requires Some New Integration And Software
- **Performance - ETR** - **160 NM/28.5° - 114 Klb**
  - **220 NM/28.5° - 109 Klb**

Figure 10. Shuttle-C (Cargo)

Shuttle qualified systems and the established Space Shuttle infrastructure to achieve the earliest possible heavy-lift capability, as well as other benefits of economy and reliability. The major new element that is required is the Shuttle-C Cargo Element (SCE). Some design and definition work is needed to develop the SCE, but it is a relatively straight forward concept . A key aspect is that it is designed to allow payloads to be interchangeable with the Orbiter. The SCE structure is built in two major elements. The forward payload carrier is an easily manufactured aluminum skin-and-ring frame fuselage. Payload bay length is 82 feet and is covered by Orbiter-like doors. The aft (boattail) fuselage is based on existing Orbiter design, minus wings, vertical stabilizer, and body flap. Although some aspects of Shuttle-C are being refined, the design is well understood. The SRBs and ET are identical to those in the inventory, which reduces costs and minimize disruptions in the Space Shuttle program. The Main Propulsion System (MPS) is also identical to the current Orbiter MPS. Two SSMEs are used for payloads up to 100,000 pounds to low Earth orbit, with three used for payloads in excess of 100,000 pounds. SSME's used by Shuttle-C will have seen as many as nine missions on the Orbiters and will complete their life cycle on Shuttle-C. The on-orbit propulsion is provided by an aft reaction control system (RCS) based on the Orbiter design. The Orbiter's maneuvering engines are not needed, and the remaining thrusters will be configured to meet Shuttle-C RCS requirements. The payload environment will be equal to that of the Orbiter with simpler, low-cost systems replacing the expensive, reusable Orbiter systems. Avionics/GN&C are adapted from the Orbiter; those systems required for manned support, long-duration orbit, descent, and landing will be deleted. Other SDV options being studied are inline vehicles utilizing both ET derived or SRB replacement sized liquid boosters, hybrid boosters, and recoverable propulsion/avionics modules. Potential evolution paths of the various SDV options are shown in Figures 11 and 12.

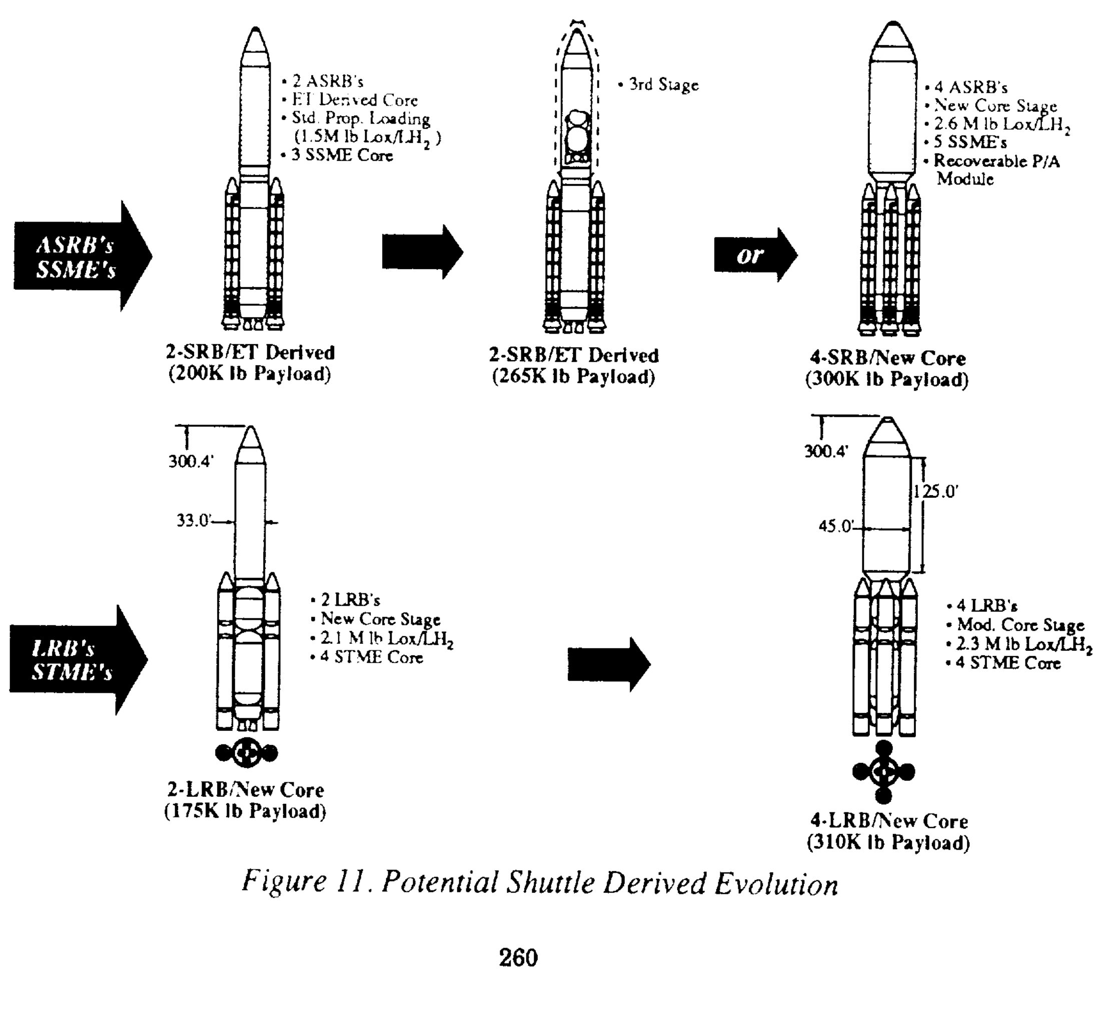


Figure 11. Potential Shuttle Derived Evolution

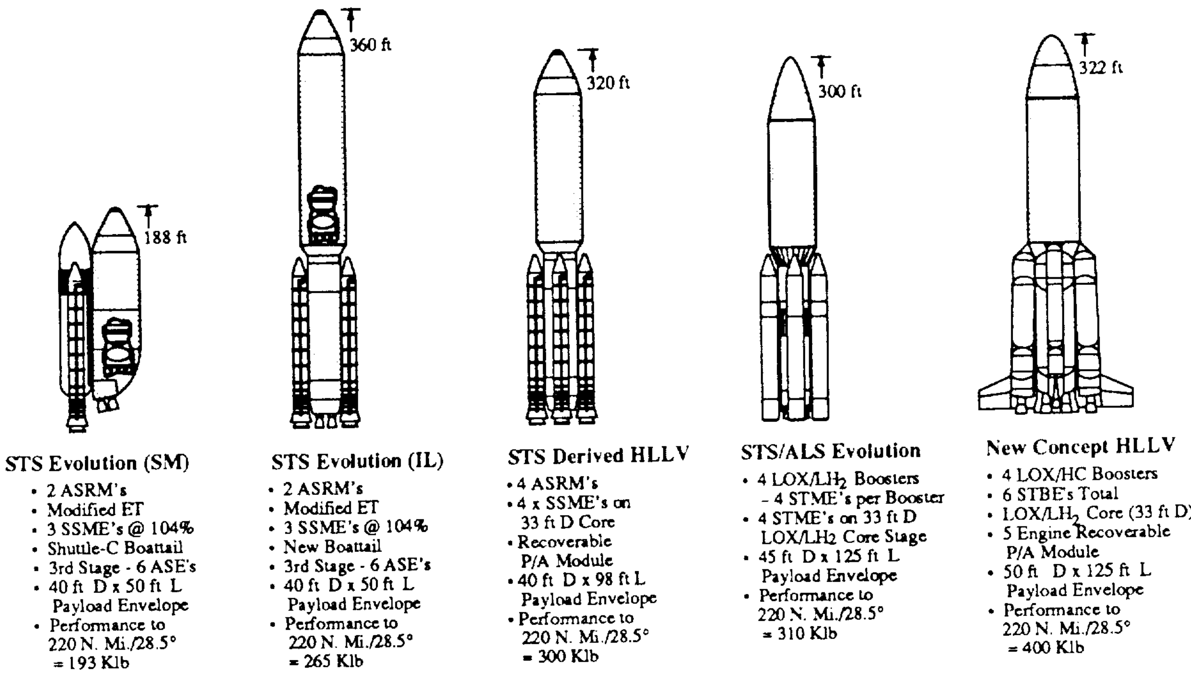


Figure 12. Shuttle Derived Heavy Lift Launch Vehicles

The ALS program, a joint AF/NASA effort, is conducting both studies and advanced development activities to determine a family of unmanned vehicles required to meet future mission needs. The range of payload lift capability to LEO being investigated is from approximately 40,000 to 450,000 pounds, see Figure 13. NASA has a lead role for ALS in liquid engine systems and technology. The goal of ALS is to provide a low cost unmanned payload lift capability in the range of $300 per pound to LEO.

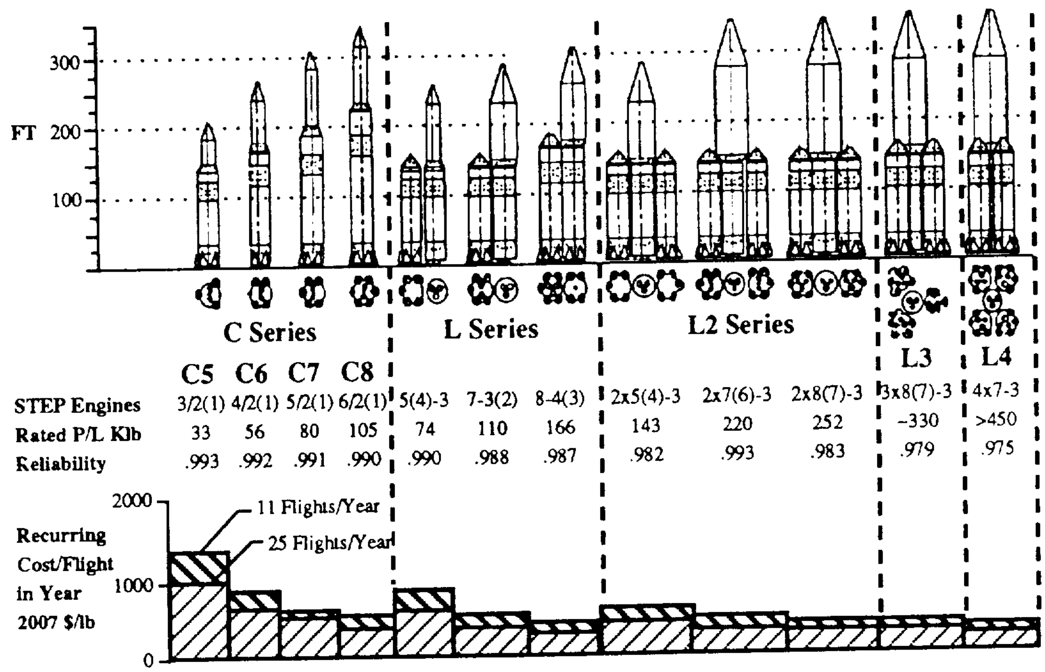


Figure 13. Advanced Launch System Family

The SEI 90-Day Study resulted in both an SDV and ALS option for satisfying the requirements for the Lunar and Mars missions, see Figures 14 & 15 respectively. The primary focus of the 90-Day Study was to provide a low DDT&E cost approach for implementing SEI. Therefore, Shuttle derived vehicles utilizing existing and growth elements were proposed. The alternative was a low operational cost philosophy for which ALS was chosen. Current efforts are underway to study alternate infrastructure approaches for satisfying the integrated ETO requirements, including both manned and unmanned launch vehicles.

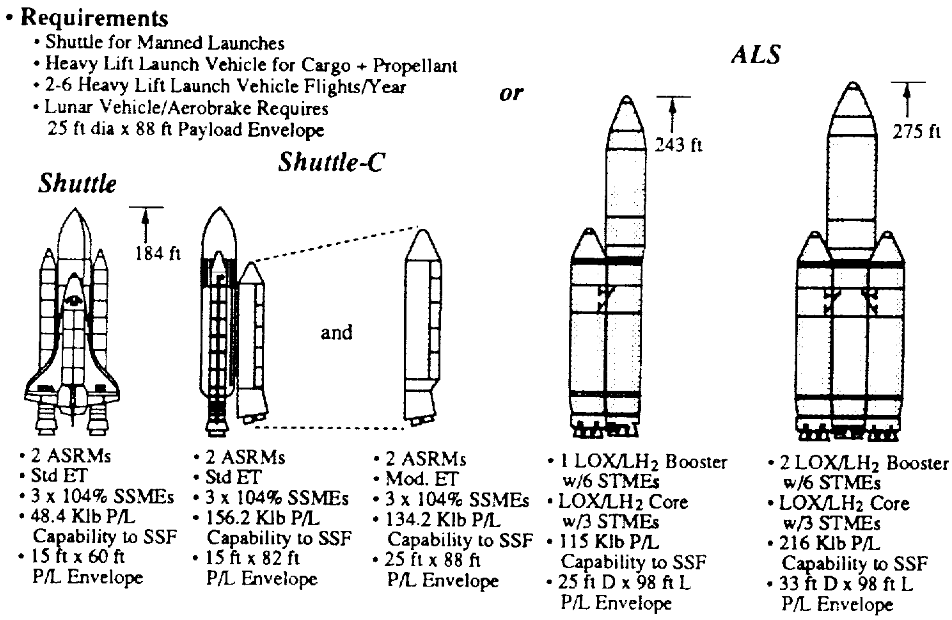


Figure 14. Launch Vehicles for Lunar Missions

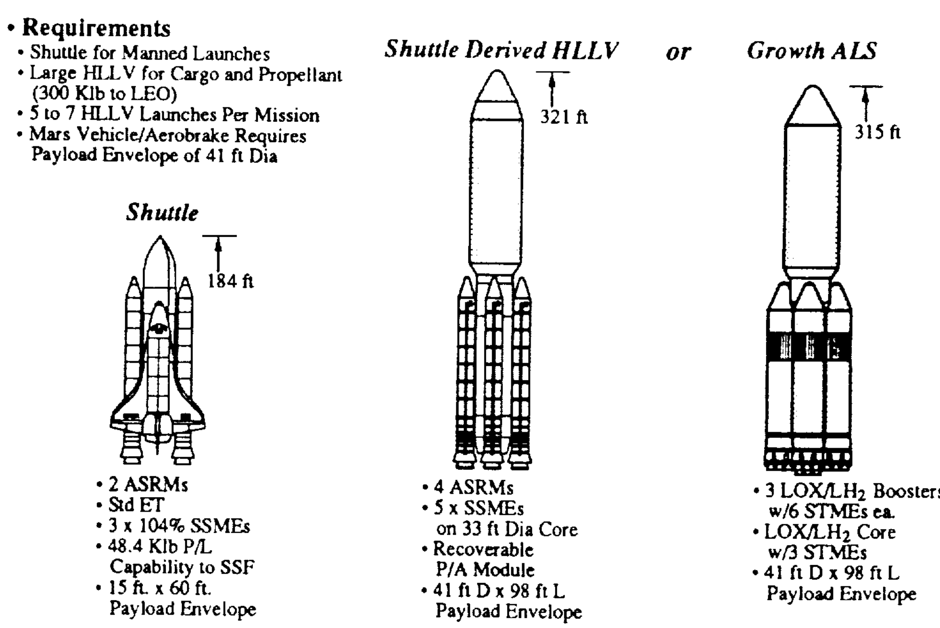


Figure 15. Launch Vehicles for Mars Missions

As previously stated, the nation's need for access to space is expected to grow significantly during the next 15-30 years. Highly efficient and flexible space transportation systems will be needed to support a number of new space initiatives currently in the planning phase. These space transportation systems will range from the current space Shuttle with planned improvements to heavy-lift launch vehicles using new booster propulsion systems operating on liquid oxygen/liquid hydrogen, liquid oxygen/hydrocarbon, and liquid oxygen/solid fuel propellants.

The National Aeronautics and Space Administration (NASA) is expected to be in the forefront of these developments and will be called upon to provide the needed technology and development. Therefore, it is imperative that NASA foster, nurture, and continue to develop its capability in the full spectrum of rocket propulsion. Potential propulsion options must be continuously explored and assessed to ensure that the most optimum systems for the particular applications are understood and characterized. In order to accomplish this, technology programs with a specific focus must be initiated in sufficient time to provide the detailed knowledge needed to make the proper selections.

Booster Options

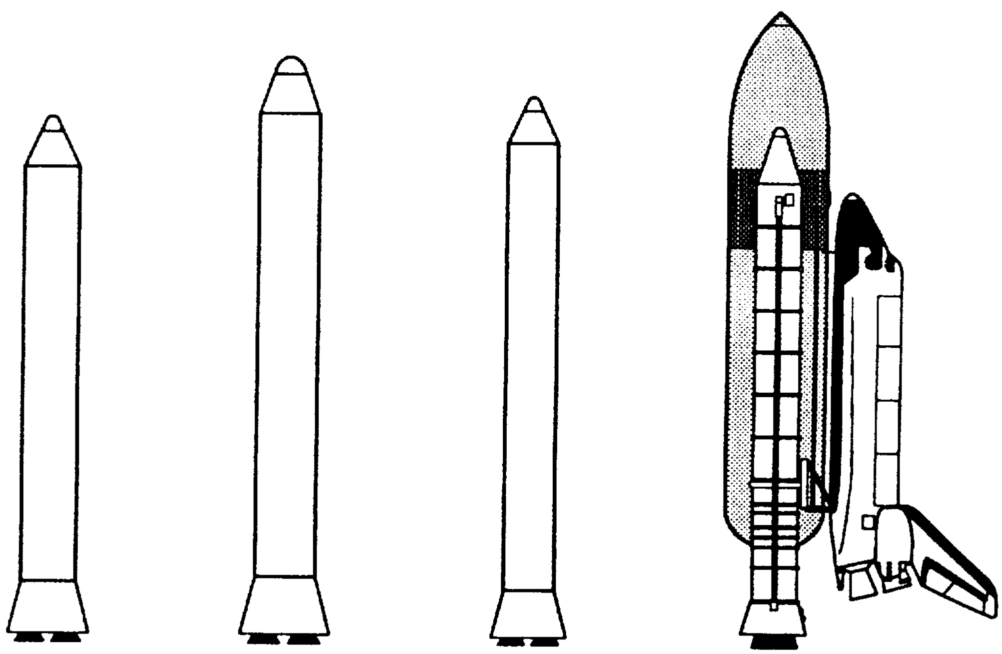
Solid Rocket Boosters have a significant flight performance database. The simplicity of their propulsion system design results in low cost and high reliability. The high propellant density of solid boosters results in the smallest system packaging for any given thrust level. This reduced envelope minimizes the booster structural cost and launch site processing facility requirements. The significant drawback of the solid rockets on the Shuttle is that no abort options are available after booster ignition and prior to motor shut down. The inability to shut down a solid motor on command precludes any first stage abort modes. In addition to limiting mission abort options, the SRB also produces combustion products which significantly impact the environment. The SRB and planned advanced SRB motor exhaust contains significant amounts of hydrochloric acid (HCl) and aluminum oxide. The HCl contributes to the acid rain problem and is suspected of reducing the ozone layer in the atmosphere. The aluminum oxide is suspected of contributing to Alzheimer disease. Because the oxidizer and the fuel are mixed and loaded in the motor cases at remote propellant manufacturing locations, special safety precautions have to be taken during SRB handling, shipping, and assembly prior to installation on the Shuttle vehicle. Extensive safety requirements increase operational costs and timeline schedules. For example, the SRB stacking activities at the vehicle assembly building (VAB) require that the building be evacuated of all unnecessary personnel during these assembly sequences.

Therefore, studies and technology activities are ongoing to provide the database and technology maturity to allow either liquid and/or hybrid boosters to be designed and built when needed. The primary study focus to date has been on boosters to replace the solids on the Shuttle. The following discussion deals primarily with boosters of that class. However, larger liquid boosters are being investigated for application to a heavy lift launch capability. The technologies described are also applicable to this class of boosters.

Liquid Rocket Boosters

While liquid rocket boosters (LRB) offer increased mission safety because they provide engine out capability and thrust termination on command, the liquid propulsion systems are more complex and costly compared to the SRBs. The unit cost estimates for the liquid booster options range from 15 to 30 percent higher than the solid boosters.

There are several LRB propulsion system options, see Figure 16. Each option has advantages and disadvantages compared to the others, and their rating of merit in various criteria, i.e. cost, reliability, etc., fluctuates such that no clear choice is available. The following paragraphs describe the more promising liquid booster propulsion system options for the Space Shuttle and summarize their pros and cons. It should be noted that the LRBs described have the performance to deliver a 70,500 lb payload to 28.5° inclination and 160 nautical miles with 75 percent engine power level (engine out capability). This greatly exceeds the SRB or proposed ASRM capability. A comparable SRB would require a motor casing diameter increase to fourteen feet.



	Pressure Fed LO_2/RP-1	Pump Fed LO_2/LH_2	Pump Fed LO_2/RP-1	SRB
Length	163 ft.	178 ft.	151 ft.	149 ft.
Diameter	16 ft.	18 ft.	15 ft.	12 ft.

Figure 16. Liquid Rocket Booster Configurations

LO_2/LH_2 Pump-Fed LRB - The LO_2/LH_2 LRB is the largest Shuttle booster option because of the low density of the hydrogen fuel. This vehicle is approximately 18 ft in diameter and 178 ft high. Because of its size, the LO_2/LH_2 booster presents the most Shuttle integration difficulties. The booster does have the advantage of common propellants with the Shuttle Main Propulsion System (MPS); and if the Space Shuttle Main Engines (SSME) were replaced with Space Transportation Main Engines (STME), the booster and MPS would have common propellants and common engines.

Current costs predictions for the liquid booster options do not show an advantage for any vehicle. However, the LO_2/LH_2 booster costs are based on the STME technology goal of $3.5M per engine. Escalated STME engine costs could require that the engines be recovered for reuse. The added system complexity and higher propulsion system costs would put the LO_2/LH_2 option at a disadvantage.

Another consideration for the pump-fed LRB options is the inherent reduced reliability for turbo machinery. STME design and operating parameters are intended to maximize the total system reliability and should result in a minimum of criticality one failure modes.

LO_2/RP-1 Pump-Fed LRB - The LO_2/RP-1 booster is the smallest selected liquid booster option for the Space Shuttle. The booster length is 151 ft and the diameter is approximately 15 ft. This booster presents the minimum Space Shuttle integration impacts of the selected LRB options. The propulsion system design is very conservative and operates at combustion chamber pressure (Pc) comparable to the F-1 engine used on the Saturn 1C launch vehicle. More optimum LO_2/RP-1 engines are a consideration which would significantly reduce the booster size. The current operational Energia LO_2/RP-1 booster engine operates at a Pc three times the proposed Shuttle LO_2/RP-1 system. This higher Isp propulsion system would make the pump-fed LO_2/RP-1 booster comparable in size to the solid booster systems.

The overall reliability of the LO_2/RP- 1 pump-fed system would still be influenced by the use of turbo machinery. The low Pc engines would have an advantage because of lower pump requirements, but require larger propellant supplies. The higher pump requirements for the more efficient LO_2/RP-1 engines would present similar reliability issues to the high pressure LO_2/LH_2 systems.

LO_2/RP-1 Pressure-Fed LRB - The pressure-fed LRB has the highest reliability propulsion system because it does not utilize turbopumps to produce the high pressure propellants which are injected into the combustion chamber. The use of high pressure (1000 psi) propellant tanks instead of pumps results in thick (1 inch) tank walls and therefore is the heaviest of the three liquid booster options. The low engine combustion chamber pressure (660 psi) also requires the highest propellant mass of the three options. However, the high density of the RP- 1 compared to LO_2 results in a lower total propellant volume than the LO_2/LH_2 booster. The pressure-fed LO_2/RP-1 LRB is 16 ft in diameter and 163 ft long.

The pressure-fed LRB requires some technology demonstration unique to this propulsion system cycle. Although many pressure-fed systems have been flown successfully, e.g. the Shuttle orbital maneuvering system, these systems are relatively small compared to the LRB. The development of systems to pressurize large propellant tanks has yet to be achieved. A second propulsion system issue is the performance of large, low Pc thrust chambers especially with high range (40%) throttle capability. These technology issues are being investigated by the Booster Technology Program at MSFC. Demonstration test articles are being designed and developed for both the pressurization system and thrust chambers. The quarter scale system testing is scheduled to be completed by 1993.

Although the pressure-fed booster costs are only slightly lower than the pump-fed systems, the pressure-fed system does not have the high cost risk associated with the $3.5M pump-fed engines. Cost proposal for full scale (750K thrust, Pc=660 psi) pressure-fed thrust chamber assembly test articles support the current cost estimates for the production of pressure-fed engines ($2.5M each). Any escalation of the pump-fed engine costs give the pressure-fed boosters a significant advantage over the pump-fed options.

Hybrid Rocket Boosters

The Phase I Hybrid Booster Technology Study was completed by four aerospace contractor teams. The study teams recommended booster options which used either a classical hybrid combustion cycle or a gas generator hybrid combustion cycle. The classical hybrid contains no oxidizer in the solid propellant grain and introduces liquid oxygen at the front end of the hybrid motor. The gas generator (GG) hybrid has a low percentage of oxidizer in the solid grain. When the GG is ignited, a fuel rich gas is produced in the motor and forced into an aft mounted combustion chamber. Liquid oxygen is injected into the aft combustion chamber to complete the fuel combustion.

The preliminary data developed in the Phase I study does not show a performance or cost advantage for either hybrid option. The vehicle size and costs are comparable to the SRB or ASRB. The discriminators between the two hybrid options are: (1) combustion cycle complexity and operating pressures; (2) manufacturing, transportation, and handling considerations; and (3) technology requirements.

Classical Hybrid Rocket Booster - The classical hybrid booster uses no oxidizer in the solid fuel. The hybrid motor is inert and presents no extraordinary manufacturing, handling, or transportation safety concerns. In addition, the combustion products of the classical hybrid are comparable to a hydrocarbon liquid fuel. The classical hybrid motor operates at approximately 1000 psia and would have motor casing design and manufacturing similar to solid rocket motor casings. Because no solid fuel and oxidizer mixing is involved in loading the motor cases, a monolithic case design case can be readily achieved for any size classical hybrid motor. The operating pressure of a classical hybrid can be achieved by either a pump or pressure-fed oxidizer system.

The key technology associated with the classical hybrid, see Figure 17, is the ability to inject liquid oxygen into the motor such that uniform combustion exists along the length of the solid fuel grain. Multiple port designs in the solid grain appear to be a promising solution, but very little testing on large motors has been accomplished to date. Ignition of the classical hybrid requires uniform oxidizer flow throughout all ports of the solid grain period. As the number of ports increase, the uniform ignition and burning throughout the fuel becomes more complex. The inability to provide uniform combustion in the motor would impact motor performance and result in numerous technical and safety issues.

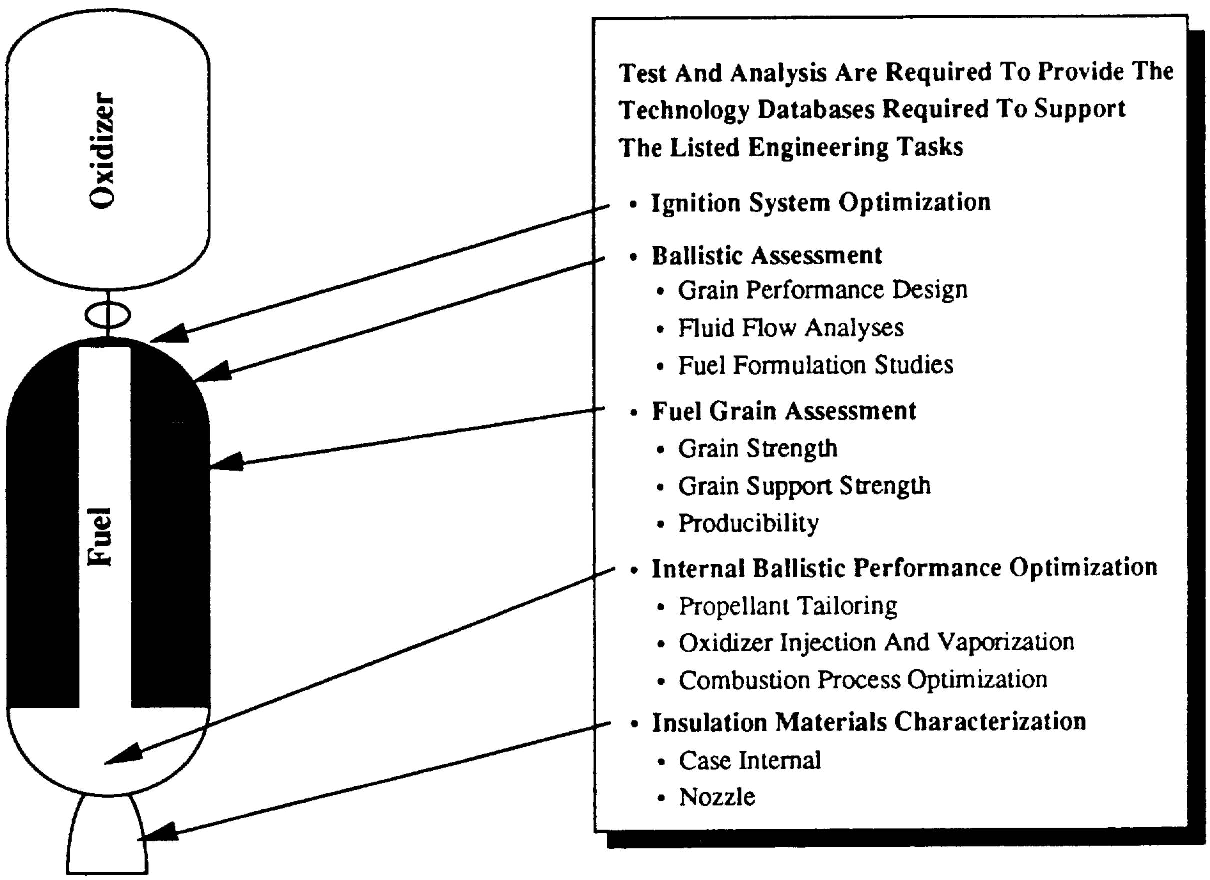


Figure 17. New Hybrid Technology Requirements

<u>Gas Generator Hybrid Rocket Booster</u> - The gas generator hybrid motor avoids the concern with uniform motor combustion by including a low percentage of oxidizer in the solid grain and injecting the liquid oxygen into the fuel rich solid motor combustion gas in a liquid rocket type combustion chamber. This combustion cycle minimizes the hybrid motor technology and relies on finely tuned liquid rocket combustion technology to provide safe, uniform, solid fuel combustion.

Data from the Phase I hybrid studies showed gas generator pressures from 1400 psi to 1870 psi. The corresponding aft combustion chamber pressures are 1000 psi to 1700 psi. The percent of oxidizer in the solid grain for all GG concepts is approximately 20% by weight. It is important to note that LO_2 engine inlet pressures significantly in excess of 1000 psi would exclude the pressure-fed liquid oxygen option from the gas generator hybrid booster. At high operating pressures, pressurization system size and complexity combined with structural mass of the oxygen tank would negate the reliability advantages of the pressure-fed system.

Low percentages oxidizer in the solid grain significantly reduce the safety concerns in solid propellant manufacturing, loading, and motor transportation and handling. However, some increased safety requirements should be expected when compared to an inert motor. The low percentage of solid oxidizer also allows the use of chemical scavengers to reduce the amount of HCl in the motor exhaust to an acceptable level. Although scavengers reduce the performance of the solid fuel, the requirement for environmentally safe combustion products will dictate their use.

As stated above, the key technology issues for the gas generator hybrid booster parallel liquid rocket combustion technology. The balance between gas generator operating pressure and aft combustion chamber pressure is critical to the safe and efficient combustion of the fuel rich gas developed in the solid motor. Well documented pressure fluctuations exist in solid motors which will greatly influence the liquid/gas combustion chamber stability requirements. The capability of the liquid oxygen pressurization (pump or pressure) control system, efficiency of the LO_2 injector, and combustion stability of the thrust chamber are key technical issues in the development of a large gas generator cycle hybrid rocket booster.

Ignition of the GG hybrid booster also presents several technical challenges. The gas generator hybrid must be ignited over a large portion of the exposed surface while the oxidizer is introduced into the aft combustion chamber. In order to have a predictable start, the two events must occur simultaneously. The thrust chamber combustion will choke the flow at the throat and communicate a back pressure to the solid grain to prevent self extinguishment. If at that time the majority of the surface of the solid grain is not ignited, the grain will not perform as intended.

Technology Programs

The primary technology programs at the MSFC relating to future transportation systems are the solid rocket motor integrity program, the liquid engine test bed, ALS technologies and the Civil Space Technology Initiative (CSTI).

The main focus of the solid rocket motor integrity program is on improvement of solid rocket motor reliability. Issues being addressed are test and verification procedures, analytical model data bases, experimental test for data, systems approach for improving reliability, process control measures and instrumentation/diagnostic capability. Specific areas being actively worked are propellants and insulation, nozzles, bond lines, combustion dynamics and integrity/verification techniques. This program has been underway since 1984, and is expected to continue through at least 1993.

The liquid engine test bed program provides off-line propulsion component and development type tests in a highly realistic cryogenic engine environment. For example, a new turbopump design can be added to an SSME test bed engine and evaluated for selected technology improvements. Specific areas of technology being addressed are combustion testing, large scale turbomachinery validation and health monitoring. The turbomachinery effort includes air and water simulation testing of flow models as well as computational fluid dynamics analyses. The health monitoring effort is particularly active in measuring engine performance and sensing actual engine operating conditions.

ALS technologies being pursued are the advanced engine program, advanced avionics program, recovery system development, composite structure development, advanced manufacturing processes and base heating analysis. The advanced engine program, the largest effort, focuses on the next generation liquid rocket engine needs and characteristics. Cryogenic hydrogen is the primary fuel being considered. A significant emphasis is on achieving a low cost engine.

A Propulsion R&T Program has been initiated that covers the specific technology needs required for the development of a pressure-fed, LO_2/RP- 1 propulsion system. Provisions for the research and development of a liquid oxidizer/solid fuel hybrid propulsion system are also included. The focus of this program is partially driven by a recognized deficiency in the technological development of pressure-fed and hybrid booster systems. This program is not only needed to correct this deficiency, but also to revitalize the nation's space program involvement in advancing rocket propulsion technology, which has languished since the Space Shuttle became operational. It will also provide much needed engineering experience to individuals replacing retired personnel who where the pathfinders in the Apollo and early Space Shuttle design efforts.

The MSFC's CSTI effort is focused in three areas: Earth-to-orbit propulsion, booster technology and the aero-assist flight experiment (AFE). The earth-to -orbit propulsion program addresses analytical models for engine environments and component life; bearing, seal and turbine blade technologies; instrumentation for engine environments; engineering testing to validate models; and component/ test bed testing. The booster technology focuses primarily on the hybrid and the pressure-fed propulsion systems.

Summary

The advent of Space Station Freedom and future anticipated Lunar and/or Mars manned explorations, the nation will require both additional heavy lift capability for unmanned payloads and enhanced capability in the manned vehicle area. More reliable and less costly transportation will be the driving force for whatever vehicles this country will decide to place into service to support its needs.

Development of technology, supporting of science and building of a sound space transportation infrastructure is cornerstone to U.S. space leadership. This nation is back on track with its launch vehicles. However, we have a far way to go to realize our plans for the future. Based on the data presented in this paper, the following major points can be made:

- The U.S. has had an extremely successful space program to date.
- Reliance on a single vehicle for transportation to orbit is unacceptable.
- Launch vehicles will never be 100% reliable, therefore one has to program and budget for eventual failure.
- The current budget environment will not allow for multiple major new starts, therefore one has to build as much as possible on existing systems.

- Major reductions in current systems' recurring costs will be required to allow new starts and maintain the funding within anticipated budget allocations.
- Future systems, both unmanned and manned, are being studied.
- A heavy lift launch capability will be required to support SEI mission requirements.
- Liquid/hybrid boosters provide an attractive alternative to solid boosters.
- Continued technology work in advanced low cost engines, pressurization systems, and hybrid combustion processes is needed to assure an adequate data base for future system implementation.

BOOSTER PROPULSION - SOLIDS